



Simulation of Heating of Oil-Cooled Switch Modules

by Gregory K. Ovrebo

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14. ABSTRACT <p>I used solid modeling and finite element fluid dynamics codes to simulate the thermal characteristics of switch modules built from silicon carbide bipolar junction transistors (BJTs) and Schottky diodes. The results of the simulation can be used in conjunction with thermal management techniques to mitigate heating of high power, high temperature electronics and minimize the risk of damage during operation.</p>					
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Contents

List of Figures	iv
List of Tables	iv
1. Introduction	1
2. Hardware Modeling	1
2.1 Switch Module	1
2.2 Oil-Cooled Heat Sink	2
2.3 Coolant Oil	4
3. Thermal Simulations	5
3.1 Steady State Simulations	5
3.2 Time-Dependent Simulations	8
4. Conclusions	13
Distribution List	14

List of Figures

Figure 1. The 10 kW switch module, as modeled in SolidWorks.	2
Figure 2. The copper heat sink attached to the switch module in the SolidWorks model.....	3
Figure 3. The heat sink box, with heat sinks attached, in a semi-transparent view. Oil inlet ports are shown on the left end of the box and outlet ports are shown on the right.	3
Figure 4. The assembled switch modules and oil-cooled heat sink used for thermal simulations in Cosmos FloWorks.....	4
Figure 5. Temperature contour plot of the heat sink and modules for a steady state thermal simulation. Oil temperature is 150 °C.....	6
Figure 6. Temperature contour plot of a switch module circuit board for the steady state simulation. Oil temperature is 150 °C.....	6
Figure 7. Temperature contour plot of the heat sink and modules for a steady state thermal simulation. Oil temperature is 80 °C.....	7
Figure 8. Oil flow and velocity through the heat sink box, side view.	7
Figure 9. Oil flow and velocity through the heat sink box, top view.	8
Figure 10. Temperature contour plot of the heat sink for a time dependent thermal simulation, t = 1 s. Oil temperature is 150 °C.....	9
Figure 11. Temperature contour plot of the heat sink for a time dependent thermal simulation, t = 3 s. Oil temperature is 150 °C.....	9
Figure 12. Temperature contour plot of the heat sink for a time dependent thermal simulation, t = 5 s. Oil temperature is 150 °C.....	10
Figure 13. Temperature contour plot of the heat sink for a time dependent thermal simulation, t = 1 s. Oil temperature is 80 °C.....	11
Figure 14. Temperature contour plot of the heat sink for a time dependent thermal simulation, t = 3 s. Oil temperature is 80 °C.....	11
Figure 15. Temperature contour plot of the heat sink for a time dependent thermal simulation, t = 5 s. Oil temperature is 80 °C.....	12

List of Tables

Table 1. Properties of the BP oil used in the computational fluid dynamics model.....	4
Table 2. Maximum surface temperatures for steady state and time dependent simulations at two oil temperatures.....	12

1. Introduction

The U.S. Army Research Laboratory (ARL) uses simulation tools that include Cosmos FloWorks, a computational fluid dynamics code, to investigate thermal management problems in high-power, high-temperature electronics. The electronic components involved in this investigation are switch modules featuring bipolar junction transistors (BJT) and Schottky diodes based on silicon carbide (SiC) dies. These modules are intended to carry loads of hundreds of amperes and so must dissipate hundreds of watts of heat. The modules are mounted on a heat sink assembly, and oil is pumped through this assembly to cool it. The task discussed in this report is to model the operation of the switch modules and their cooling apparatus to estimate the maximum temperature of the electronics.

Hardware components are modeled with SolidWorks¹ solid modeling software. Cosmos FloWorks uses the solid models to perform finite element calculations of heat transfer and fluid dynamics. I performed steady state simulations, using constant power inputs, and time dependent simulations, using power inputs which vary over time, and compared the results. I repeated the simulations with two different oil temperatures which may be available in an automotive environment.

2. Hardware Modeling

2.1 Switch Module

The first piece of hardware to be modeled in SolidWorks was the module circuit board with lands and devices. The circuit board material was designated as aluminum nitride (AlN), the circuit board lands as steel, and the BJTs and Schottky diodes as solid SiC. Only the larger features of the circuit board are used in modeling. Thin layers, like the gold plating on the circuit board lands, and fine features, like bond wires, add an extra order of complexity to the meshing of the finite element model without adding to the accuracy of the thermal simulation. This can slow the simulation or even cause it to fail if FloWorks runs out of system memory.

Six BJTs and 2 Schottky diodes were used in this model of the switching module, approximating the placement of devices on a real board. The devices are modeled only as uniform volume heat sources; no attempt is made to model the devices at the junction level, nor is there any circuit modeling like that in Spice.

¹SolidWorks is a registered trademark of Solid Works Corporation.

Figure 1 shows the layout used in modeling the circuit boards. The BJTs are the smaller devices, shown in green, and the Schottky diodes are larger and shown in blue.

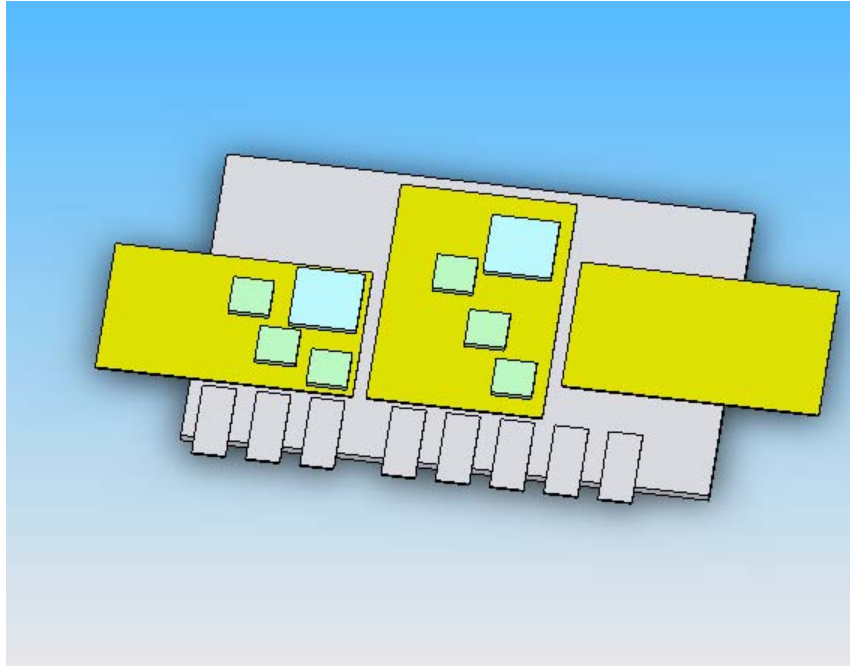


Figure 1. The 10 kW switch module, as modeled in SolidWorks.

2.2 Oil-Cooled Heat Sink

A copper heat sink is attached to the bottom surface of each of the circuit board modules described above. The base of the heat sink is 1.5 inches (38.1 mm) square. The heat sink had 40 pins, each 0.72 inches (18.3 mm) long and 0.07 inches (1.8 mm) in diameter, which extend into the coolant oil to increase heat transfer from the switch modules.

Figure 2 shows a rendering of one of the copper heat sinks, as modeled in SolidWorks.

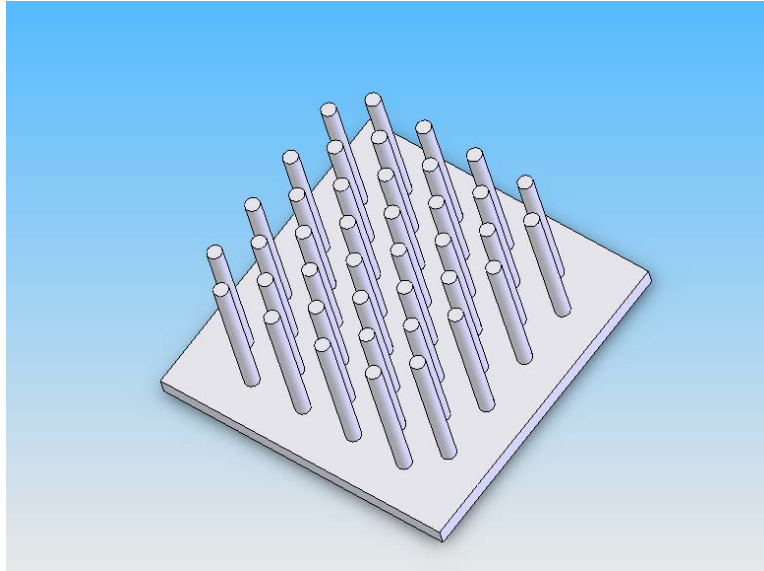


Figure 2. The copper heat sink attached to the switch module in the SolidWorks model.

The heat sinks are inserted, pins down, into a metal box channeling the flow of synthetic oil which draws heat away from the modules. The box material was modeled as copper. The oil is pumped into two ports at one end of the box, flows over the heat sink pins, and flows out the ports at the other end of the box.

Figure 3 shows the assembled heat sink box, with the top and bottom of the box made semi-transparent to show the heat sinks inside.

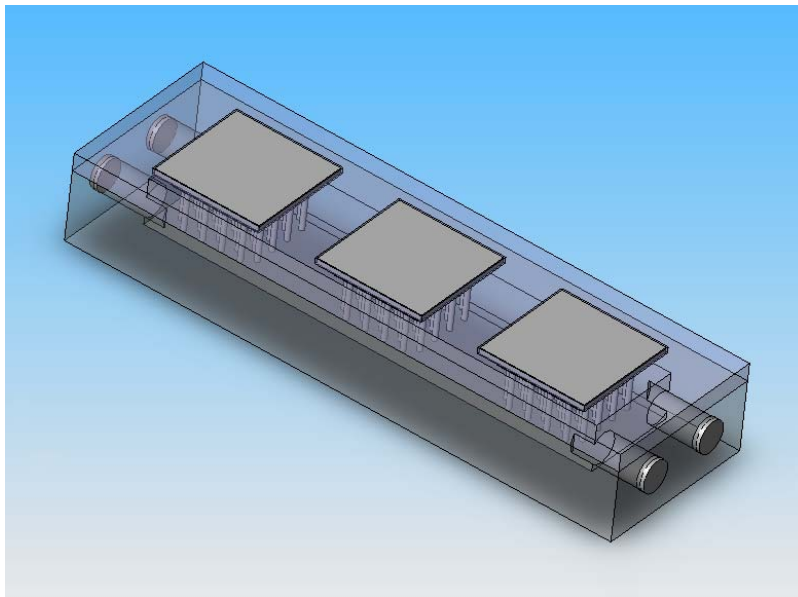


Figure 3. The heat sink box, with heat sinks attached, in a semi-transparent view. Oil inlet ports are shown on the left end of the box and outlet ports are shown on the right.

Figure 4 shows the assembled test fixture, with circuit boards mounted on the heat sinks and the heat sinks inserted into the oil-cooled box. This is the solid model used for thermal simulations in Cosmos FloWorks.

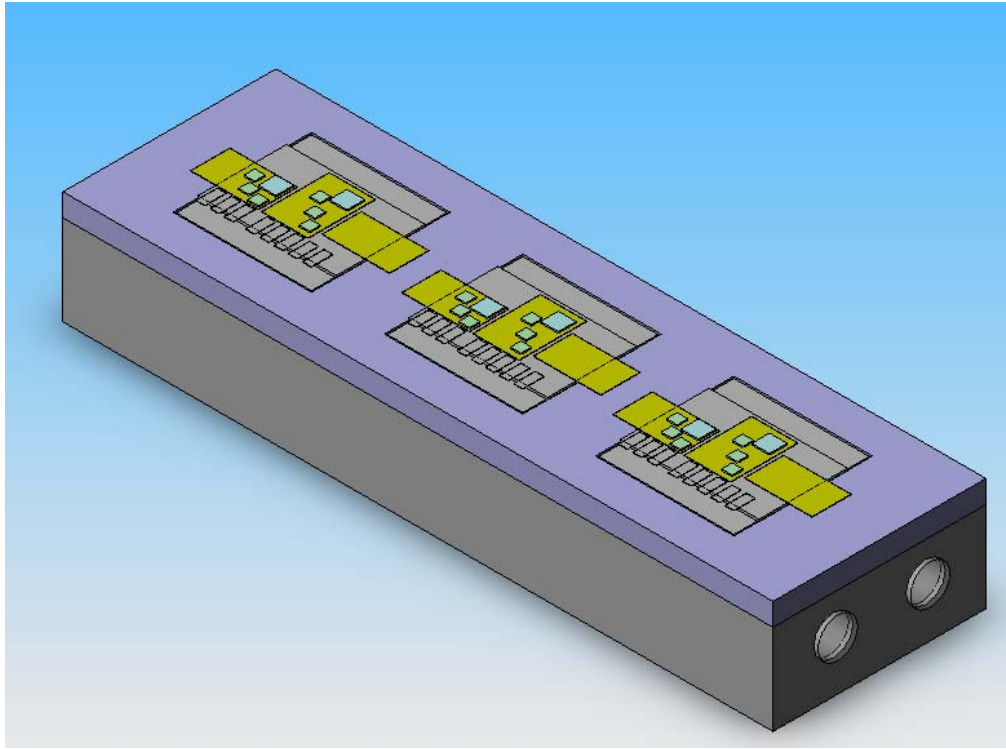


Figure 4. The assembled switch modules and oil-cooled heat sink used for thermal simulations in Cosmos FloWorks.

2.3 Coolant Oil

In these simulations, I used a BP synthetic oil as a model for the engine oil which would be used as a coolant in this switch module assembly. Temperature dependent properties of the oil, including density, dynamic viscosity, specific heat, and thermal conductivity, were added to the FloWorks material database. The table below gives extrapolated values for these quantities at 80 °C and 150 °C, the simulated operating temperatures.

Table 1. Properties of the BP oil used in the computational fluid dynamics model.

Property (units)	80 °C	150 °C
Density (kg/m^3)	909.0	859.5
Dynamic viscosity (Pa·s)	0.00469	0.0019
Specific heat ($\text{J/kg}\cdot\text{K}$)	2140.8	2265.4
Thermal Conductivity ($\text{W/m}\cdot\text{K}$)	0.1485	0.1456

3. Thermal Simulations

I performed a series of thermal simulations with the 10 kW switch module model, using both steady state and time dependent configurations. The steady state calculations assumed a constant level of heating from the SiC devices. The time dependent calculations used a time-varying heating function, simulating the first five seconds of physical time after the devices turned on. I performed these simulations for two different oil temperatures, 80 °C and 150 °C. These represent the highest and lowest temperatures which might be available in a hot automobile engine.

In all of the following thermal simulations, some factors remained constant. I assumed that oil flowed at a rate of 3 gallons per minute through the heat sink box. Each inlet port carried half the flow. All heat transfer was by means of conduction from the circuit board to the heat sink, and from the heat sink to the oil. I assumed no radiation or air convection from the heat sink box or circuit boards. The ambient temperature of the assembly, before device heating, was specified to be the same as the oil temperature.

3.1 Steady State Simulations

The steady state simulation modeled each SiC device as a constant volume heat source. The BJTs produced 33.3 W each, totaling 200 W for each of the three modules. The Schottky diodes produced 25 W each, totaling 50 W for each of the three modules. These numbers were derived from requirements for the six BJTs to carry a total of 60 amperes with a 3.3 V drop, and for the two Schottky diodes to carry a total of 15 amperes with a 3.3 V drop. Each steady state simulation required only a few minutes of CPU time.

Figure 5 shows a contour plot of the calculated temperatures on the assembly surface, assuming a flow of 150 °C oil at 3 gpm. The maximum temperature calculated in this simulation is approximately 250 °C, an increase of 100 °C above the ambient temperature.

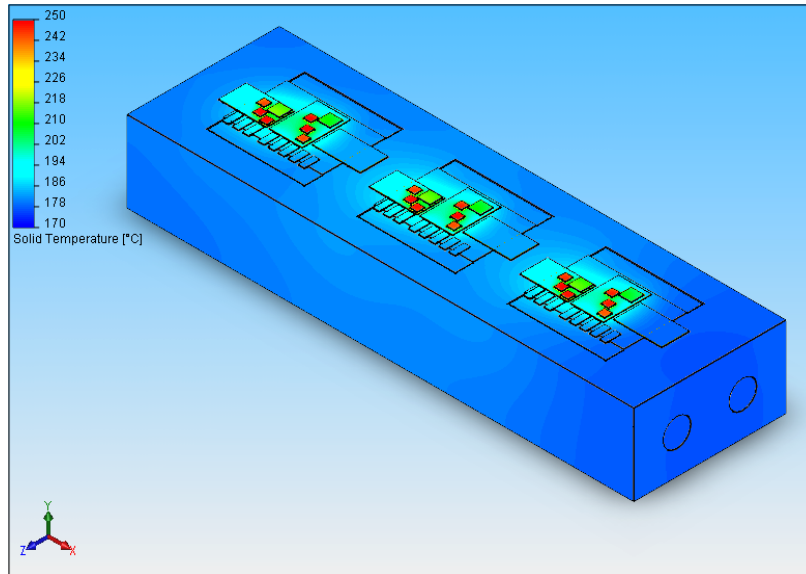


Figure 5. Temperature contour plot of the heat sink and modules for a steady state thermal simulation. Oil temperature is 150 °C.

Figure 6 shows a close-up view of the temperature contours on a switch module board for the steady state simulation described above. This particular board is the leftmost unit on the heat sink assembly in figure 5.

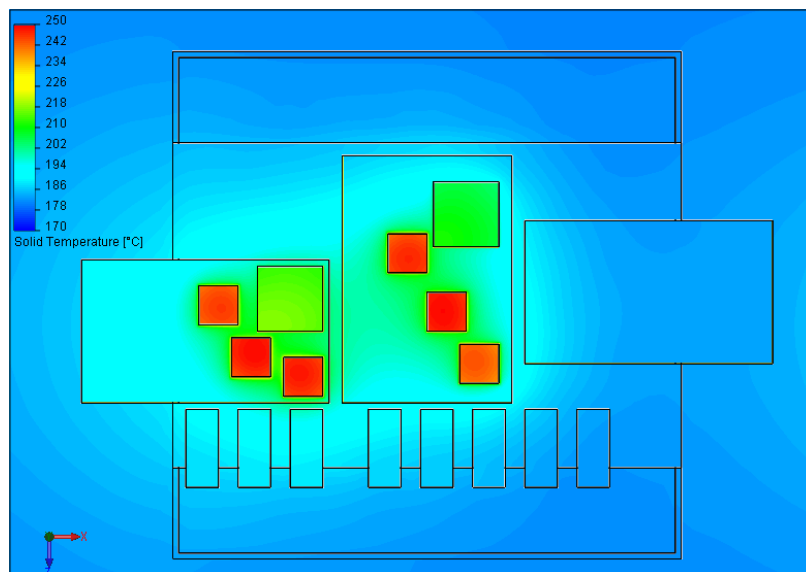


Figure 6. Temperature contour plot of a switch module circuit board for the steady state simulation. Oil temperature is 150 °C.

Figure 7 shows a contour plot of the calculated temperatures on the assembly surface, assuming a flow of 80 °C oil at 3 gpm. Again we see an increase of 100 °C above the ambient temperature of the oil, with a maximum temperature of 180 °C on the BJTs.

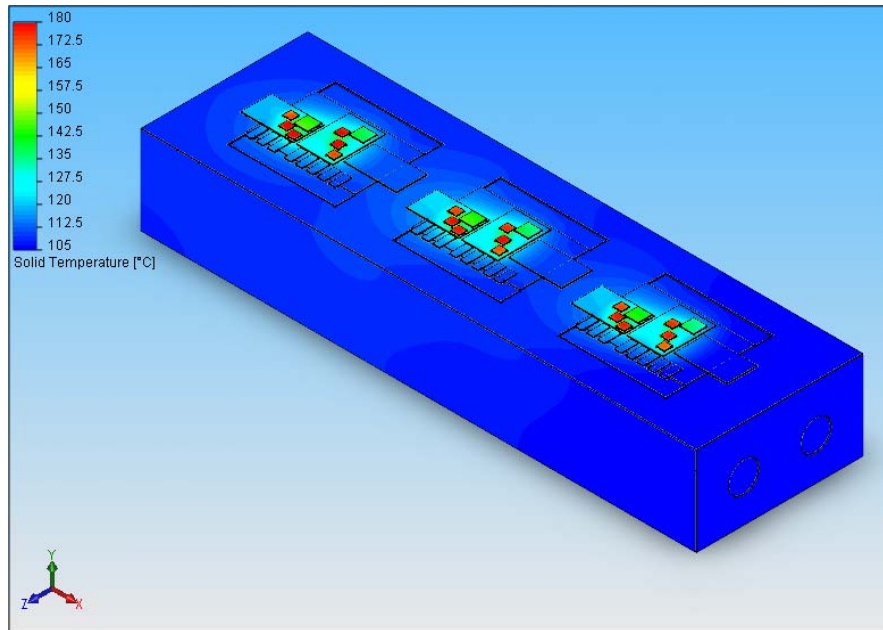


Figure 7. Temperature contour plot of the heat sink and modules for a steady state thermal simulation. Oil temperature is 80 °C.

FloWorks also provides us with information about the flow of oil through the heat sink box. Figure 8 shows a diagram of oil flow through the box as a function of fluid velocity, as seen from the side of the box. Figure 9 shows the same flow of oil through the box, as seen from above the box. The flow trajectories indicate that the oil flow is unhindered and that there is good contact between the oil and the copper heat sink.

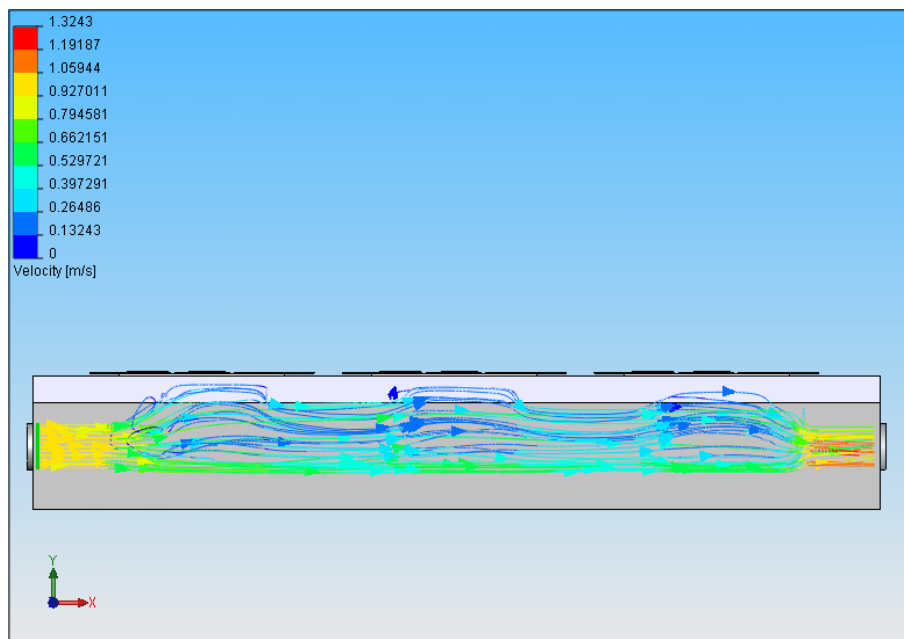


Figure 8. Oil flow and velocity through the heat sink box, side view.

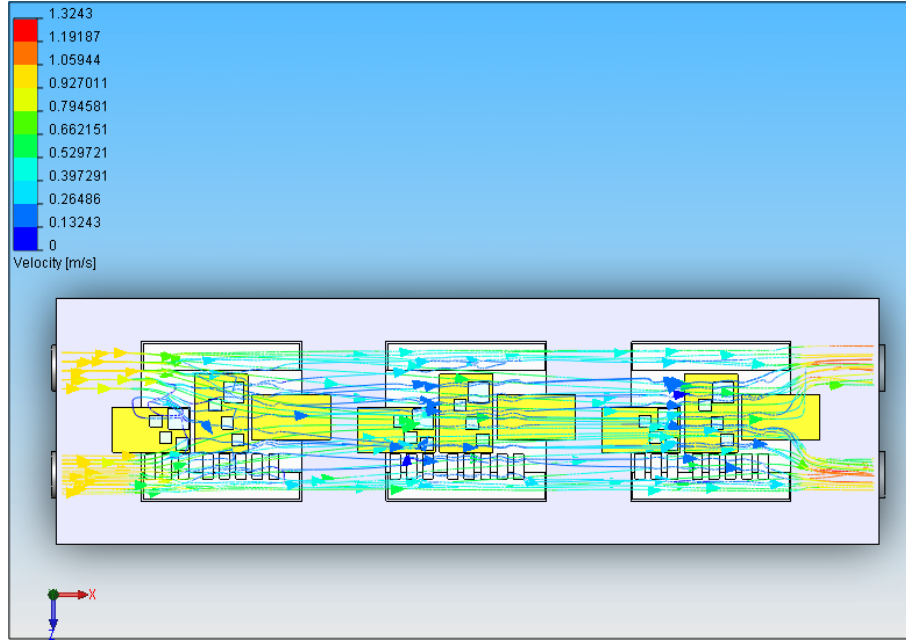


Figure 9. Oil flow and velocity through the heat sink box, top view.

3.2 Time-Dependent Simulations

The devices on the circuit board are driven by a 2 kHz signal with a 50% duty cycle; the BJTs are on while the Schottkys are off, and vice versa. The devices are modeled as uniform volume heat sources which are on for 500 microseconds at a time. When they are on, the BJTs generate 33.3 W each, while the Schottkys generate 25 W each while they are on. Thus, the total heat generated by the BJTs on each module is 200 W, while the Schottkys on each module generate 50 W. I simulated the first five seconds of operation of the switch modules, assuming that the entire apparatus, electronic modules and heat sink, had already reached the temperature of the oil before being turned on.

Simulating just five seconds of physical time required running the simulation overnight; time dependent simulations tend to be much slower than steady state simulations. The time dependent simulations may generate several gigabytes of data, depending on how frequently one chooses to record interim results during the simulations.

Figures 10, 11, and 12 are contour plots of the temperatures calculated on the surface of the boards and heat sink assembly after 1 second, 3 seconds, and 5 seconds of operation, respectively. This simulation used 150 °C oil as a coolant. I observed during the simulation that the maximum temperature on the assembly surface had peaked within about 3 seconds of operation.

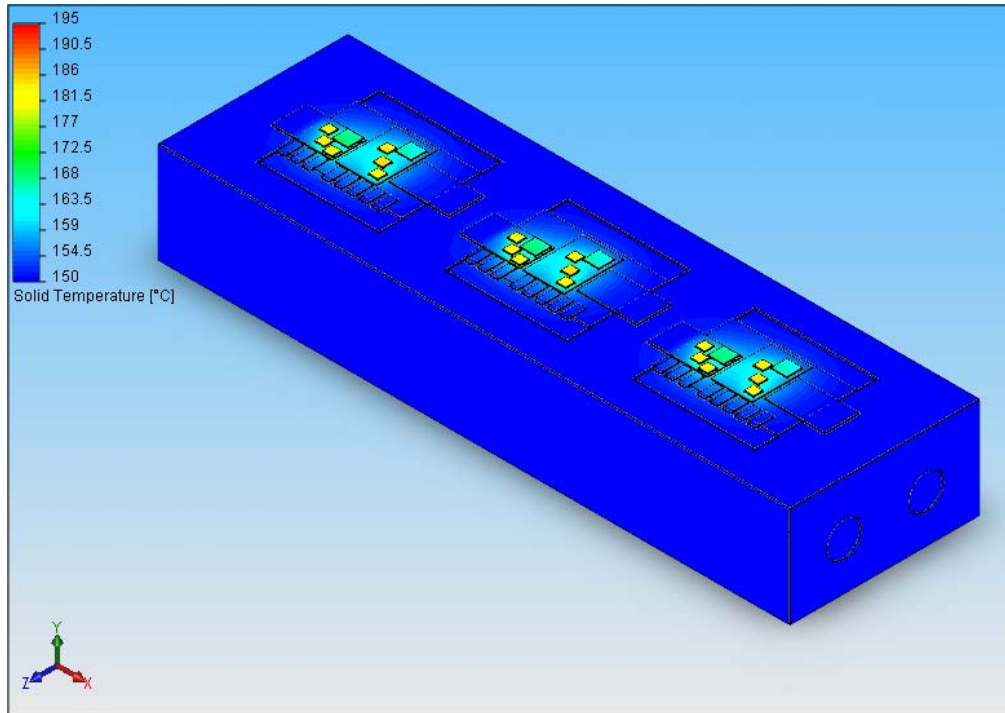


Figure 10. Temperature contour plot of the heat sink for a time dependent thermal simulation, $t = 1$ s. Oil temperature is 150 °C.

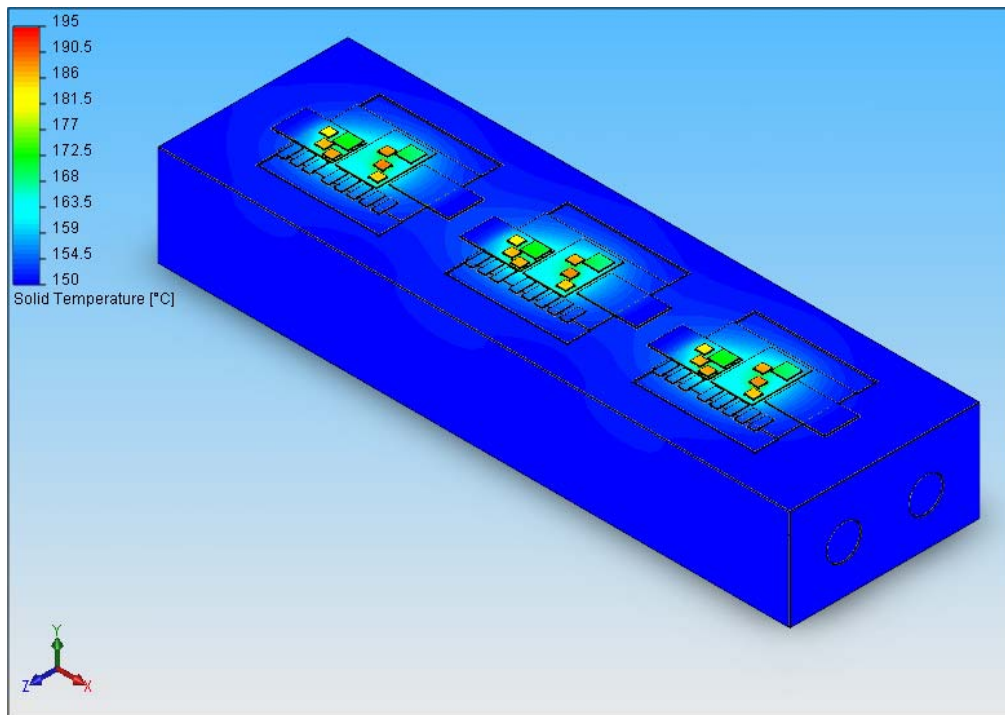


Figure 11. Temperature contour plot of the heat sink for a time dependent thermal simulation, $t = 3$ s. Oil temperature is 150 °C.

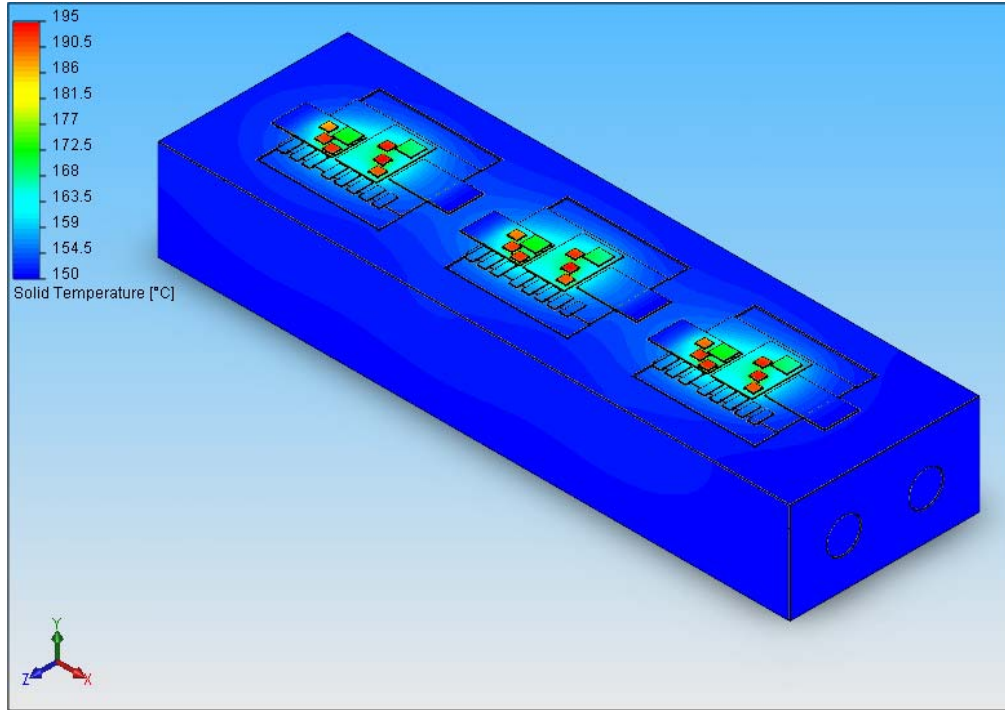


Figure 12. Temperature contour plot of the heat sink for a time dependent thermal simulation, $t = 5$ s. Oil temperature is 150°C .

The maximum temperature reached during the simulation was approximately 195°C on the BJTs, an increase of 45°C above the ambient temperature of 150°C . This is half the increase seen in the steady state simulation. This seems reasonable, considering that we are putting power into the SiC devices only half of the time in this simulation.

The second time dependent simulation also covered the first 5 seconds after the switching modules are turned on, but reduced the oil temperature from 150°C to 80°C . The other parameters and time varying heat function were unchanged from the 150°C simulation. Figures 13, 14, and 15 show contour plots of the surface temperature at 1 second, 3 seconds, and 5 seconds, respectively, after turning on.

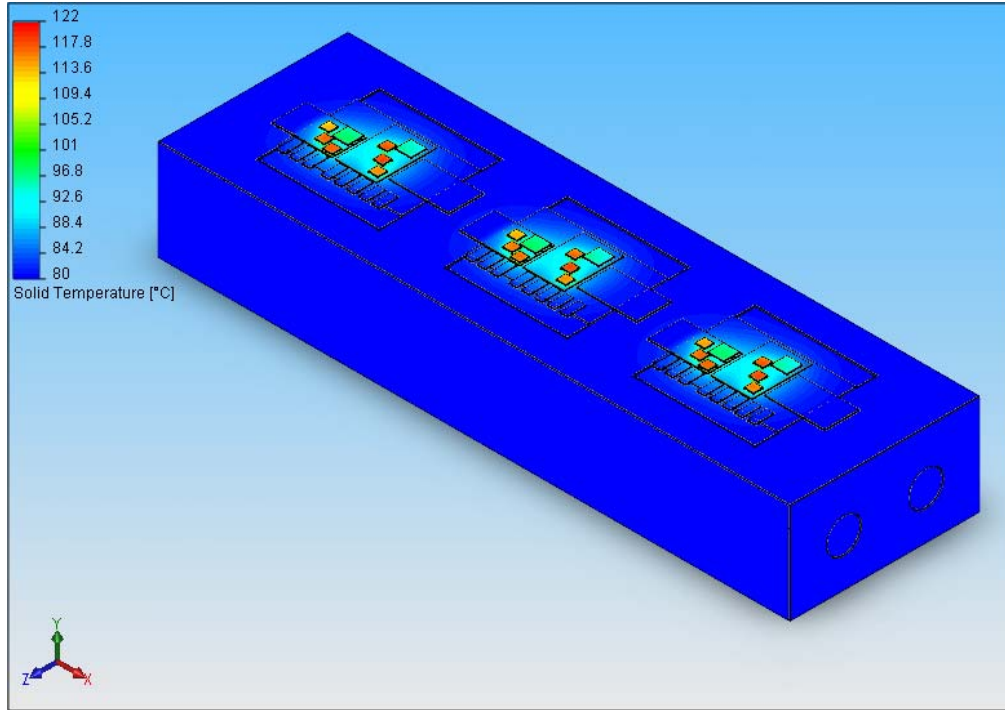


Figure 13. Temperature contour plot of the heat sink for a time dependent thermal simulation, $t = 1$ s. Oil temperature is 80 °C.

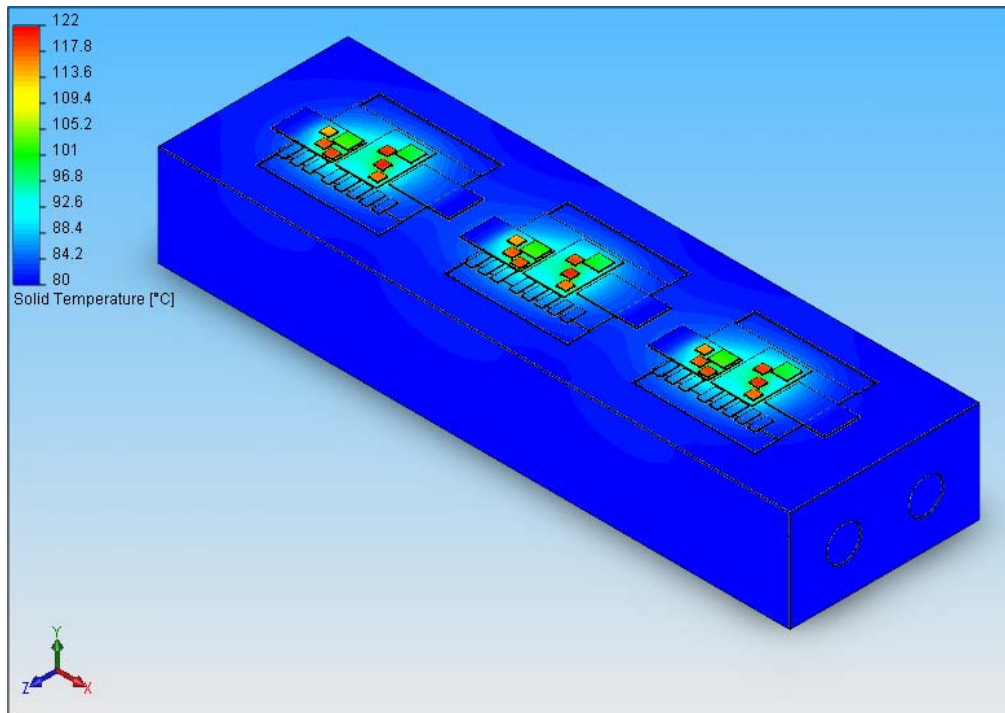


Figure 14. Temperature contour plot of the heat sink for a time dependent thermal simulation, $t = 3$ s. Oil temperature is 80 °C.

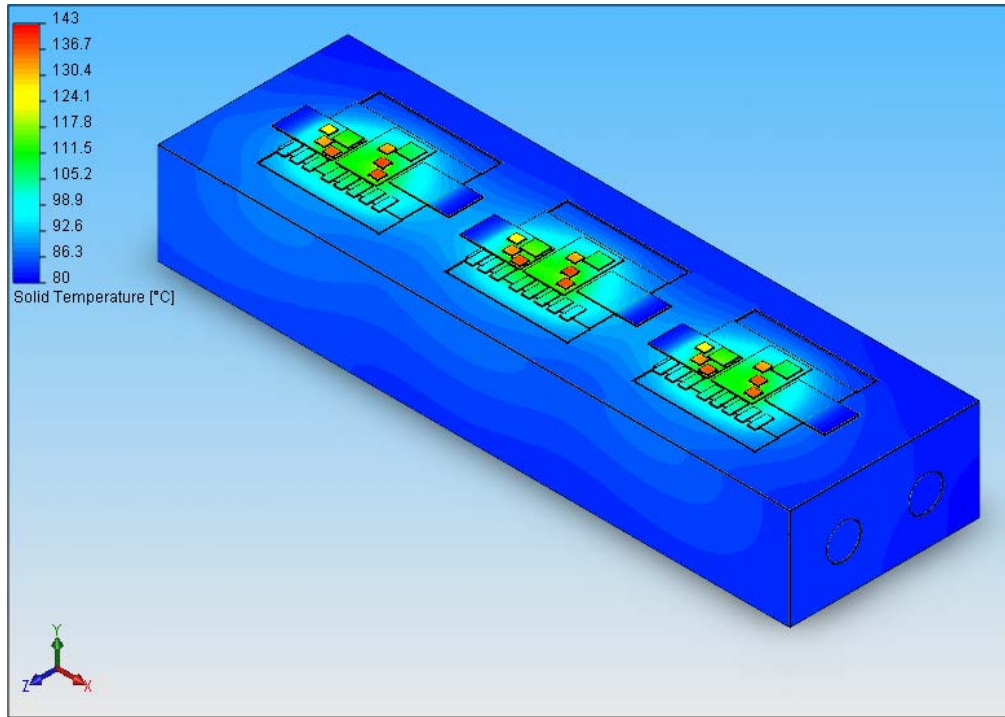


Figure 15. Temperature contour plot of the heat sink for a time dependent thermal simulation, $t = 5$ s. Oil temperature is 80°C .

The maximum surface temperature achieved was approximately 122°C . At three seconds, the BJTs had reached their maximum temperature. However, at the end of the 5 second simulation period, it appeared that parts of the heat sink box around the circuit boards were still warming. The maximum increase above ambient temperature was 42°C , about the same as the increase we saw in the 150°C simulation.

The maximum surface temperatures for the four simulation described here are summarized in table 2.

Table 2. Maximum surface temperatures for steady state and time dependent simulations at two oil temperatures.

Oil temperature	80°C	150°C
Steady state simulation	180°C	250°C
Time dependent simulation	143°C	195°C

4. Conclusions

These simulations can be used in conjunction with experimental results, such as temperature data obtained from thermocouple measurements or thermal cameras. Temperature data on the switch module boards can be used to verify and refine these computer simulations, allowing us to adjust input values for heat sources (BJTs and Schottky diodes) to better reflect real world conditions. In addition to predictions of maximum temperature on the boards, we can also use these results to predict temperature differences between points on the boards. Temperature measurements may be made with thermocouples mounted some centimeters from the hottest points on the circuit boards; FloWorks simulations provide us with an estimate, from contour plots like figure 6, of the temperature difference between the devices and the thermocouple location.

Both time dependent simulations show the same increase of 40-45 °C above the initial temperature. Both simulations appear to reach an equilibrium temperature very quickly, within 5 seconds. Because the boundary conditions for the time dependent simulations more closely resemble actual operating conditions than steady state parameters, these calculated results should be closer to laboratory data than steady state simulations.

The temperature increase calculated in steady state simulations (essentially a 100% duty cycle) is roughly twice that calculated in the time dependent simulations, which use a 50% duty cycle to simulate the function of the SiC components. Thus, the time dependent simulations seem consistent with the steady state simulations. Both time dependent simulations show a maximum temperature below 200 °C. If the temperature of the electronics climbs much above 200 °C, catastrophic failure is possible. Even the steady state simulation using 80 °C oil as coolant stayed below the 200 °C mark. Only in the steady state simulation using 150 °C oil as coolant, clearly a worst-case simulation, did the maximum component temperature climb above 200 °C. On balance, there is reason for optimism that these switching modules can be used successfully with an oil-cooled heat sink.

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